Latest results on galactic sources obtained with the MAGIC telescope

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The MAGIC telescope is the largest single-dish Imaging Atmospheric Cherenkov Telescope (IACT) with the lowest energy threshold among the current generation of IACTs as low as 25 GeV. Therefore, the MAGIC telescope is a perfect instrument to study the galactic sources especially in the context of observations with the satellite observatories Fermi and AGILE. This paper will give an overview of the MAGIC results on the galactic sources including detailed observations of binary systems, supernova remnants and the first detection of the Crab pulsar above 25 GeV .

1. Very high energy gamma-ray astrophysics with the MAGIC telescope

The Very High Energy (VHE) gamma-ray astrophysics has grown significantly with the newest generation of Imaging Atmospheric Cherenkov Telescopes (IACTs). Their high sensitivities allow to discover tens of VHE sources including galactic objects like supernova remnants, pulsar wind nebulae, binary systems, and the extragalactic active galactic nuclei, gamma-ray bursts and starburst galaxies. The standalone MAGIC telescope, as the largest single-dish IACT with the lowest energy threshold among the current generation of IACTs, contributed significantly to this field. Its energy threshold of 55 GeV with the standard trigger can reach 25 GeV with the innovative analog Sum Trigger guaranteeing a good overlap between the VHE ground-based Cherenkov telescopes and the new generation of HE satellites. This is a remarkable fact in the context of multi-wavelength studies.
The MAGIC telescope, located on the Canary island of La Palma on the Roque de los Muchachos Observatory at 2250 m a.s.l, has a sensitivity of ~ 1.6 % of the Crab flux in 50 hours of observations and an energy resolution around 15% at energies above 200 GeV. From autumn 2009 on, a second MAGIC telescope allows stereoscopic observations [1]. Thus, the sensitivity has improved substantially and will enable a deeper view of our Galaxy possible.
This paper presents an overview of the latest results from galactic observations. The latest results on the extragalactic sources are described elsewhere in these proceedings [2].

2. Galactic sources

The MAGIC telescope has detected VHE emission from 9 galactic objects: Crab Nebula, the Galactic Center, HESS J1813, HESS J1834, the SNRs Cassiopeia A and IC443, the X-ray binary LSI 61+303, the unidentified EGRET source TeV 2032 and the Crab pulsar. On top the MAGIC collaboration found an evidence of signal from the microquasar Cyg-X1. This paper highlights MAGIC contributions to the Galactic astrophysics in the last two years.

2.1. Crab pulsar and nebula

The Crab pulsar (PSR B0531+21), detected by EGRET up to 5 GeV, had never been detected in the VHE domain above 100 GeV by any IACT. The low energy threshold of MAGIC combined with the novel analog Sum Trigger developed by MAGIC has allowed to lower the energy threshold down to only 25 GeV; hence to detect the Crab pulsations in the high energy domain for the first time[19].
A sample of 22.3 h of good quality data taken in winter 2007/2008 has been selected to perform the analysis of the pulsed emission and simultaneous optical observations have been used to verify the absolute arrival time of the photons. The two signal regions have been selected a priori by using the definition of the main pulse (P1) and the inter-pulse (P2) given by EGRET [20] and the background has been estimated from the remaining events outside the these intervals. In this way a significance of 6.4 σ has been obtained above 25 GeV. P1 and P2 have similar amplitudes at E = 25 GeV, in contrast with the measurements at lower energies (E > 100 MeV) where P1 is dominant [21]. The data sample shows a small excess (3.4 σ) above 60 GeV for P2, which is consistent with our previous Crab observation [4]. This reveals a trend of P2/P1 increasing with energy: it is < 0.5 at 100 MeV, $\simeq$ at 25 GeV and > 1 at 60 GeV. This trend provides valuable information for theoretical studies which will constrain the location of the emission region in the pulsar magnetosphere.
To evaluate the energy cutoff, an extrapolation of the EGRET data has been performed by assuming two different cutoff shapes. By assuming an exponential cutoff the measured signal is compatible with an energy cutoff of E = 17.7 $\pm$ 2.8 $\pm$ 5.0 GeV. In case the cut off is super-exponential the estimated cut off energy is E = 23.2 $\pm$ 2.9 $\pm$ 8.8 GeV. The high values obtained for the cutoff strongly disfavored the polar cap model.

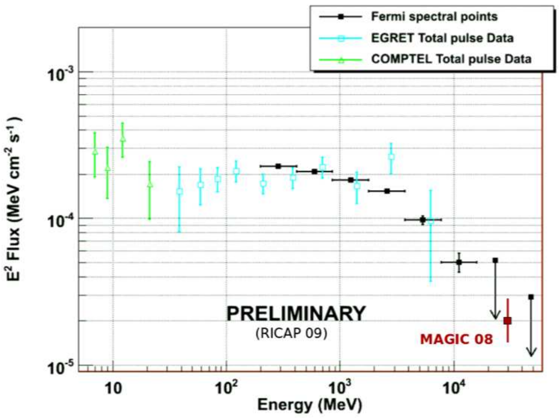

Figure 1: Crab pulsar spectrum calculated by the Fermi collaboration together with one flux point obtained by MAGIC.

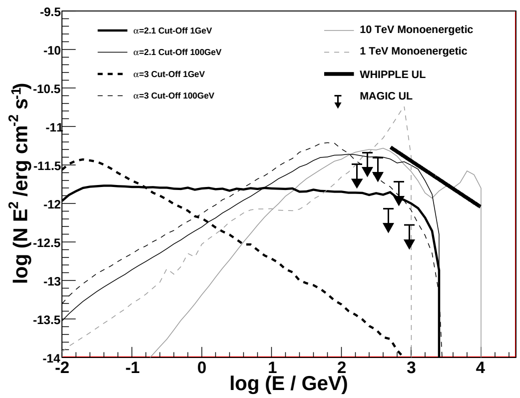

Figure 2: The MAGIC γ-ray flux upper limits for M13 compared with spectra expected for the range of parameters of the Bednarek & Sitarek's model [6].

The Crab pulsar has been detected recently by the Fermi collaboration which estimates a spectrum cut-off at $5.8 \pm 0.5 \pm 1.2$ GeV [21] (see fig. 2.1). The flux calculated by MAGIC at GeV is consistent with the extrapolation of the Fermi spectrum. Nevertheless the cutoff is marginally consistent with the Fermi one also taking into account the systematic errors.

The Crab Nebula is a pulsar wind nebula considered as the standard candle of the VHE γ-ray astrophysics due to its incredible brightness. Thanks to its low energy threshold the MAGIC experiment measured the Crab Nebula spectrum down to 60 GeV. The spectrum follows a curved power law which is consistent with inverse Compton emission. The obtained spectral energy distribution suggests the position of the inverse Compton peak at 77 ± 47 GeV[4]. This position can be better determined with the new array of two MAGIC telescopes and it will be of great importance also for the cross calibration between the IACTs and the Fermi satellite.

2.2. Globular clusters

Globular Clusters (GC) are compact groups of old stars and evolved objects like MilliSecond Pulsars (MSP). GCs have been predicted to produce TeV γ-rays by accelerated leptons scattering off photons of the microwave background radiation or the thermal emission of the star population inside the GC. Acceleration of leptons could take place either in the shocks coming from the collisions of the winds of MSPs or inside the pulsar inner magnetosphere.
MAGIC observed the globular cluster M13,located at a distance of 7 kpc, where 5 MSPs has been detected by now. The observation was carried out for 20.7 hours in June and July 2007 [5]. No signal has been found either in correspondence to the center of M13 position or in a region of 1 degree of radius around the source itself for an energy range extending from 140 GeV to 1.1 TeV.
The obtained integral flux upper limit for energies above 200 GeV is $5.1 \times 10^{-12}\text{cm}^{-2}\text{s}^{-1}$. It has been calculated at 95% CL by using the Rolke method and assuming a spectral index of -2.6. The obtained result compared with the theoretical spectra calculated in Bednarek & Sitarek's model [6] (see fig. 2.2) suggests that either the number of MSPs in M13 is significantly lower than the estimate of ~ 100, or the conversion efficiency from MSPs to relativistic leptons is significantly below the theoretical predictions of the models of the high energy processes in MSP magnetosphere.

2.3. Supernova Remnants

SuperNova Remnants (SNR) are believed to be the acceleration sites of galactic cosmic rays. Therefore, they were expected to produce VHE γ-rays as confirmed by the current generation of IACTs.
In 2007 and 2008 the MAGIC telescope performed a deep observation on Tycho and the Crab Nebula and shorter observations on various selected radio SNRs [3].
Tycho is a young shell-type SNR which is expected to be located at 3.5 kpc. It shows 8' diameter both in X-rays and radio frequencies, making it almost a point-like source for Cherenkov telescopes. Its VHE emission has been predicted by the Non Linear Kinetic (NLK) theory of cosmic ray acceleration in SNRs. In such models the dominant mechanism is the π_0 decay, rather then inverse Compton, which, however, cannot be ruled out. The MAGIC telescope observed this source for 70 hours between July and November 2007 without detecting any VHE emission above 350 GeV. The integral flux upper limit, calculated at

Table I Integral flux upper limits (3σ) for a point-like source located at the center of the observations (not necessarily the center of the SNR) for E > 270 GeV.

Source	Integral Flux UL $\mathrm{ph cm^{-2} s^{-1}}$	Integral Flux UL Crab units
HB-9	1.60×10^{-11}	11%
W51	1.26×10^{-11}	9%
CTB-80	3.56×10^{-11}	25%
W63	3.36×10^{-11}	24%
W66	6.68×10^{-11}	5%
HB-21	7.88×10^{-11}	6%
G085.4+0.7	2.58×10^{-11}	18%
G085.9-0.6	2.10×10^{-11}	15%
CTB-104A	1.40×10^{-11}	10%

99.9% CL, corresponds to $\sim$2% of the Crab flux at the same energy ($1.86\times10^{-12}\mathrm{ph cm^{-2} s^{-1}}$). This non-detection suggests that Tycho is more distant than the expected 3.5 kpc in the context of the NLK theory.
The MAGIC collaboration has selected also 8 good SNR candidates from the Green Catalogue of SNRs according to the following criteria: i) Flux at 1 GHz larger than 49 Jy; ii) radio spectral index lower than 0.6; iii) distance smaller than 7 kpc; iv) age lower than 50000 y. The selected SNRs, HB-9, W51, CTB-80, W63, W66, HB-21, CTB-104A, G85.9-0.6 and G85.4+0.7, were observed for a time varying from 5 to 10 hours each. No point-like emission has been found from any of the selected SNRs and the integral flux upper limits (3σ) for energies above 270 GeV are shown in table I. In case of W51 a hint of signal at the level of 3σ (pre-trail) has been found in correspondence to the MILAGRO J1923.0+1411 source.

2.4. Binary Systems

2.4.1. LSI +61-303

The binary system LSI +61-303 consists of a compact object and a B0V main sequence star with circumstellar disc. It displays a periodic emission from radio to X-rays with a period of 26.496 d which is believed to be associated to its orbital period. The MAGIC collaboration, after the discovery of the variable emission from the system [7], carried out a deeper observation of the object covering 4 orbital cycles. The total observation time is about 166 hours. This huge data set has shown that the TeV emission, extending up to 3 TeV, is periodic with a periodicity of 26.8 d, in good agreement with the measurements in other wavelengths. The peak of the emission has always been found at orbital phase around 0.6-0.7 (close to the apoastron). During December 2006 a secondary peak has been detected at phase 0.8-0.9. This proves that there is a certain degree of variability from cycle to cycle. Nevertheless, no VHE emission has been detected in correspondence to the periastron (phase 0.3) where the GeV emission has shown its peak [9]. The anti-correlation between TeV and GeV has been found also in the similar system LS5039 [10] [11].
Two multi-wavelength campaigns were organized in 2006 and 2007 involving radio, X-rays, VHE γ-rays observations. From these observations the existence of large scale persistent radio-jet can be excluded. An evidence of radio and TeV non-correlation has been found [12] and a significant correlation between TeV and X-rays has been proven thanks to the truly simultaneous data of the second campaign [13]. The computed correlation coefficient is $r=0.81^{+0.06}_{-0.21}$ (see fig. 3). The peak of the TeV and X-rays emission occurs at the same phase 0.62 and it has a similar shape at both wavelengths. Moreover, there is significant activity at phases 0.8-1.0 at both bands.

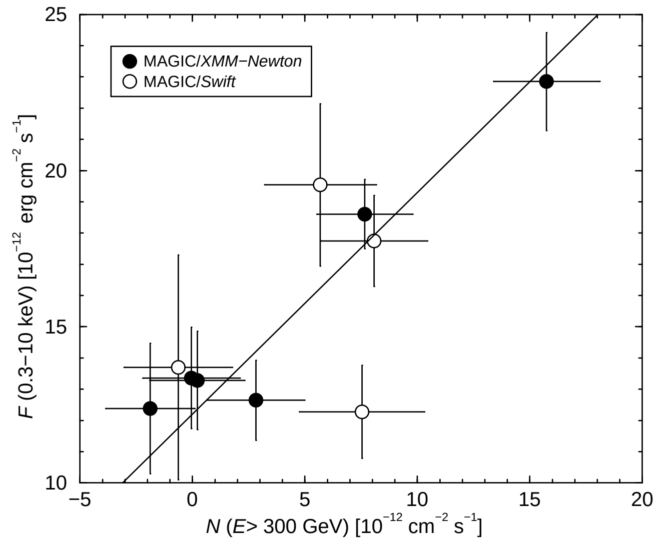

Figure 3: LSI +61 303. De-absorbed X-ray fluxes as function of VHE γ-ray fluxes. Error bars correspond to a 1σ CL in all cases.

2.4.2. Microquasars

MicroQuasars (MQ) are X-ray binary systems displaying relativistic jets driven by accretion onto a compact object. Thanks to their morphological analogies with the distant quasars, they were considered good candidates as VHE sources. Nevertheless, only a hint of signal (at the level of 4.1σ post trial) from the well-established MQ Cyg-X1 has been found by the MAGIC collaboration during a short flare on September 24, 2006 [14]. This TeV flare was coincident with the raising edge of a hard X-ray flare. The MAGIC collaboration kept on observing Cyg-X1

Table II Microquasar observations with the MAGIC telescope described according to the used observational trigger.

Source	Date	Obs. trigger	Time
Cyg-X1	2007	low/hard state	21h
	2008	super-orbital modulation	50h
GRS1915	2005-2006	radio alerts	15h
	2007	low/hard state	12h
Cyg-X3	2006	radio alerts	20h
	2007	low/hard state	35h
	2008-2009	AGILE alerts	14h

in the following years: in 2007 the source was observed when it was in the low/hard state; in 2008 it was observed during the maximum of the super-orbital modulation predicted by Rico[15]. No signal was detected so far in this second data sample. Also the phase-pholded analysis of the sample has not shown any hint of signal[16].
The MAGIC telescope observed other three MQs, Cyg-X3, SS433 and GRS1915+105 between 2005 and 2009 for a total amount of 125 h. Cyg-X3 and GRS1915+105 observations were performed according to a different observational trigger criterium every year. In 2005 and 2006 the observations were triggered by using multi-frequency information through radio flare alerts with the Russian radio telescope RATAN-600. In 2007 the Low/Hard state of the sources by using SWIFT-BAT and RXTE-ASM public data was ensured. In 2008 and 2009, only Cyg-X3 was triggered by GeV alerts from the Italian satellite AGILE. A part from 2008 and 2009 data, whose analysis is still ongoing, the results on the previous observational campaigns have not shown any signal and the calculated integral flux upper limits at 95% CL for energies above 250 GeV are at the level of 1 % Crab flux for both sources [16].

2.4.3. Wolf-Rayet Binary Systems

Wolf-Rayet (WR) stars represent an evolved stage of hot ($T_{\rm eff} > 20000$K), massive stars characterized by strong winds. The colliding winds of massive star binaries are predicted to produce VHE γ-rays through leptonic and hadronic processes. Nevertheless, this prediction has never been proven.
The MAGIC telescope observed for the first time two isolated WR star binaries[17]: W146 for 44.5 h between 2005 and 2007, and W147 for 30.3 h in 2007. Searches of γ-rays from these two objects have given no positive results for energies above 80 GeV. The integral flux upper limits at 95% CL are 1.1×10^{-11} ph cm^{-2} s^{-1} (1.5% Crab flux) and 3.5×10^{-11} ph

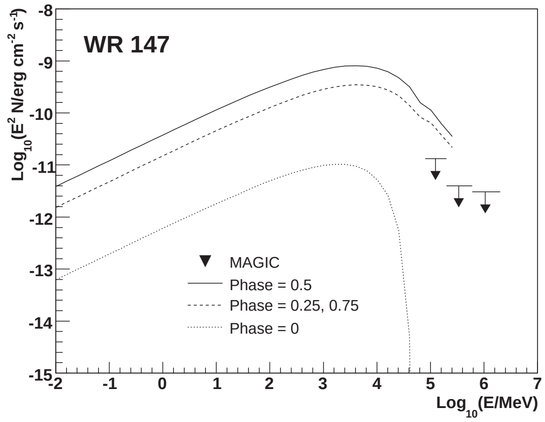

Figure 4: Inverse Compton spectra of W147 for orbital phases 0,0.25,0.5,0.75 from [18]. The γ-ray flux at phase 0.25 and 0.5 is reduced by $< 0.3\%$ and $< 18\%$ respectively as a result of absorption of γ-rays in stellar radiation in $\gamma - \gamma - e^{\pm}$ pair production process. No absorption takes place at phase 0. MAGiC upper limits are marked.

cm^{-2} s^{-1} (5% Crab flux) respectively for W147 and W146. According to this result, the Reimer's model for W147 [18] can be excluded for most of the orbital phases (see fig. 4).

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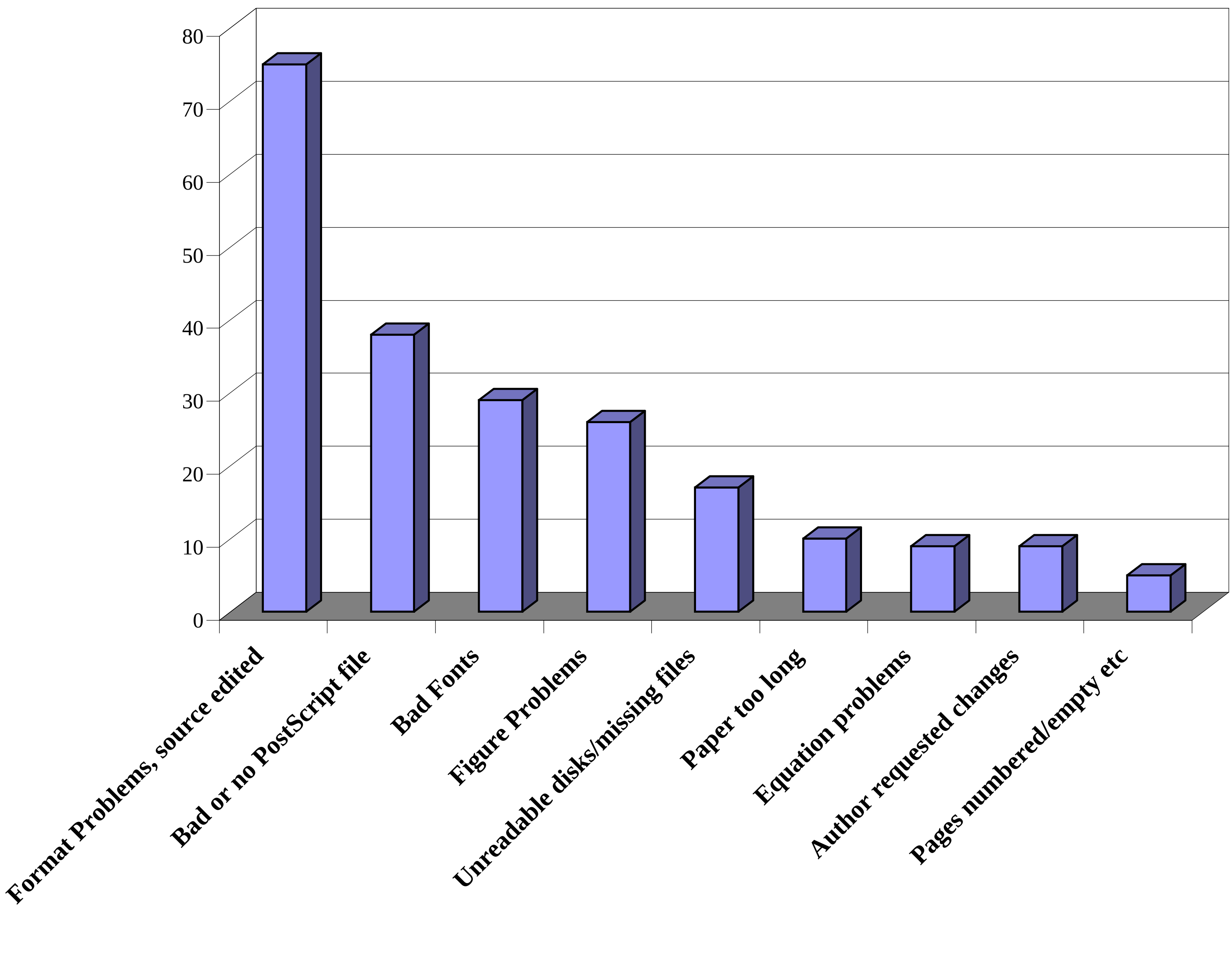

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